```
x0_4#5, mem#9 = sub_100005964() @ me
if (x0_4#5 != 0) then 68 else 69 @ 0
```

```
x0_5#6, mem#10 = sub_1000
if (x0_5#6 != 0) then 71
```

```
x0_6#7 = &var_48
x0_7#8, mem#11 =
if (x0_7#8 == 0)
```

Get to Know Your Decompiler

0x41con 2023

@jonpalmisc

About me

@jonpalmisc

- Florida man
- Long-time programmer
- Low-level & security enjoyer
- Present: iOS stuff at <private>
- Past: Binary Ninja developer at Vector 35 for 2 years

History of decompilers

A concise, biased perspective

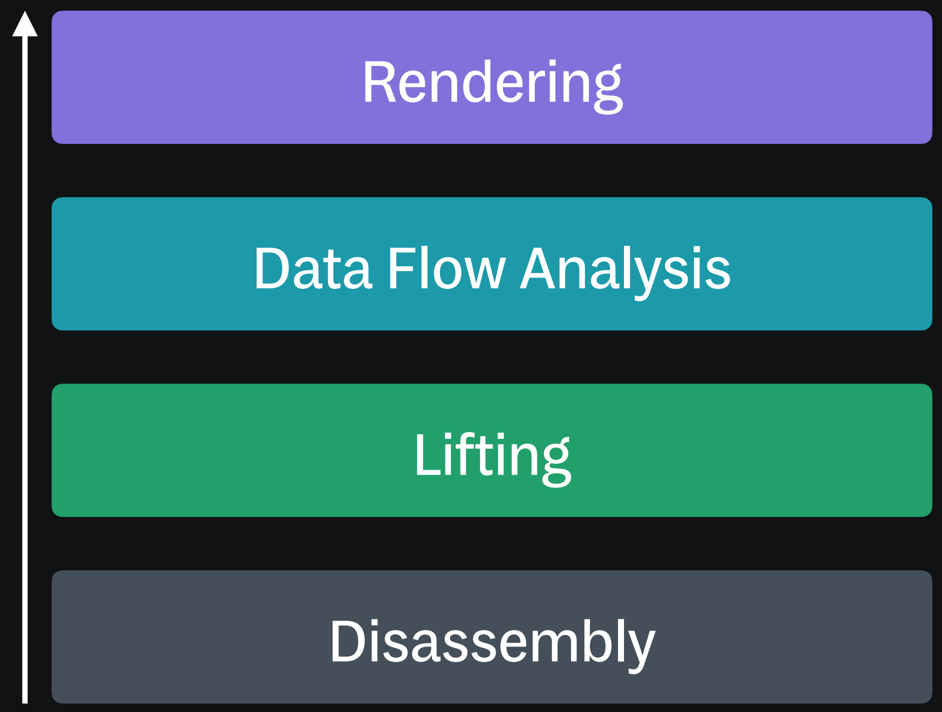
- 1994: “Reverse Compilation Techniques”
- 1995–2006: The Dark Ages
- 2007: Hex-Rays Decompiler
- 2019: Ghidra
- 2020: Binary Ninja HLIL

Decompilation stages

Overview

Decompilation stages

Overview


Rendering

Data Flow Analysis

Lifting

Disassembly

Decompilation stages

Disassembly

- Natural prerequisite for decompilation
- More than just producing text

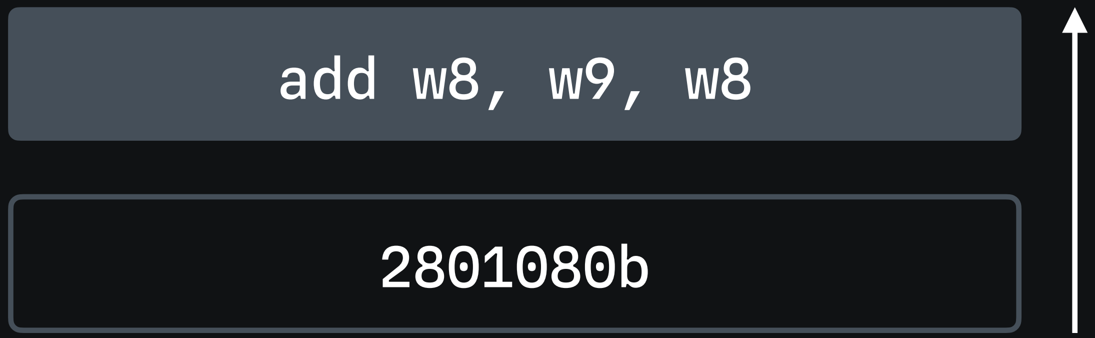
```
2801080b
```

Decompilation stages

Disassembly

- Natural prerequisite for decompilation

- More than just producing text



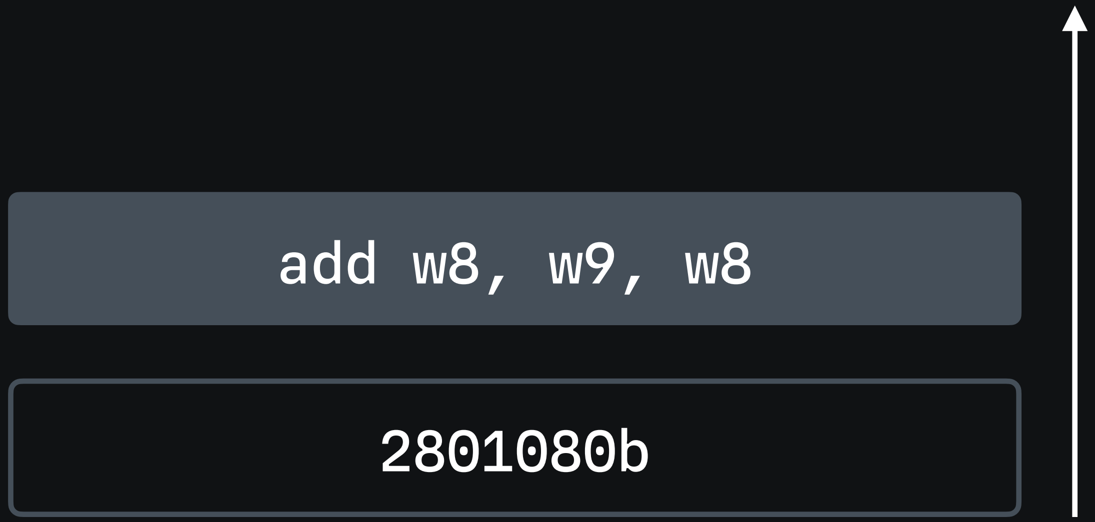
`add w8, w9, w8`

`2801080b`

Decompilation stages

Lifting

- Start abstracting machine code
- Need some intermediate representation
    - Numerous different approaches exist



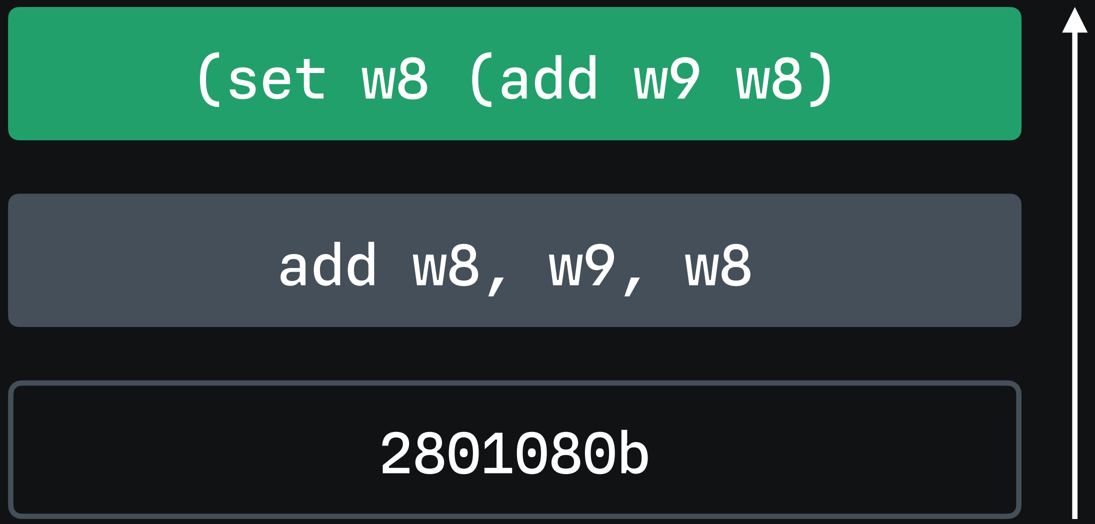
```
add w8, w9, w8
```

```
2801080b
```

Decompilation stages

Lifting

- Start abstracting machine code
- Need some intermediate representation
    - Numerous different approaches exist



`(set w8 (add w9 w8)`

`add w8, w9, w8`

`2801080b`

Decompilation stages

Data flow analysis

- Where are values defined and used?
- What are the possible values of X at address Y?
- Inherent part of decompilation internally

`(set w8 (add w9 w8)`

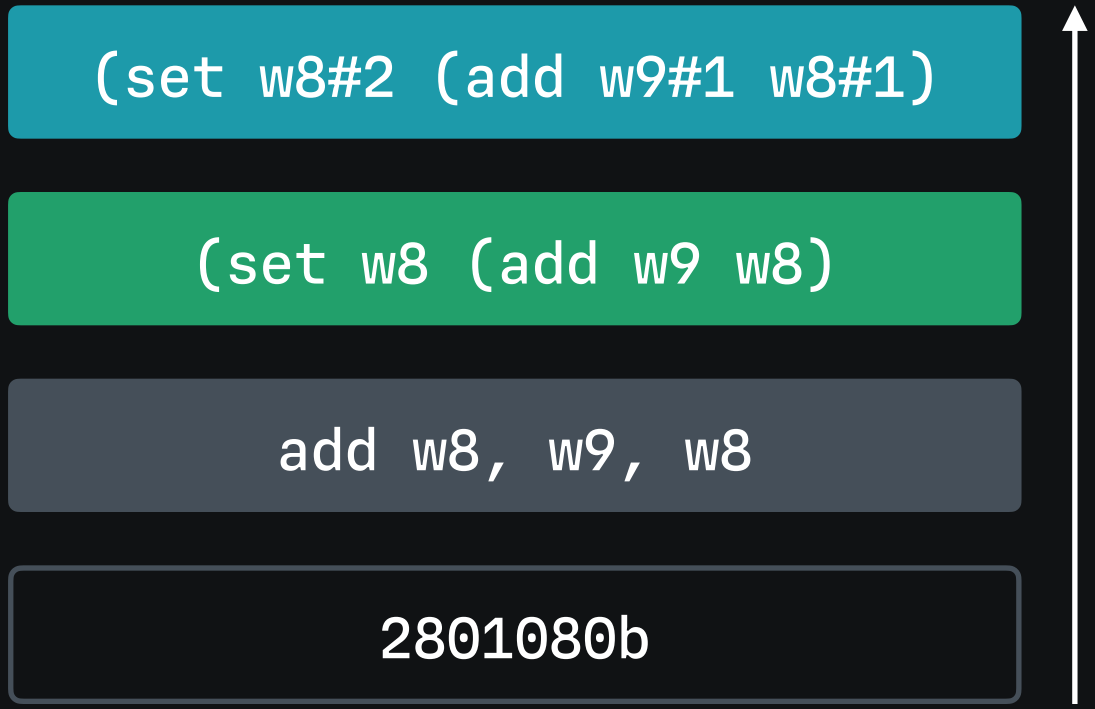
`add w8, w9, w8`

`2801080b`

Decompilation stages

Data flow analysis

- Where are values defined and used?
- What are the possible values of X at address Y?
- Inherent part of decompilation internally



```
(set w8#2 (add w9#1 w8#1)
```

```
(set w8 (add w9 w8)
```

```
add w8, w9, w8
```

```
2801080b
```

Decompilation stages

Rendering

- Need to represent the abstracted code somehow
    - C-flavored syntax has become the norm
- Not “trivial”, but less difficult

```
(set w8#2 (add w9#1 w8#1)
```

```
(set w8 (add w9 w8)
```

```
add w8, w9, w8
```

```
2801080b
```

Decompilation stages

Rendering

- Need to represent the abstracted code somehow
    - C-flavored syntax has become the norm
- Not “trivial”, but less difficult

```
int v1 = w8 + w9;
```

```
(set w8#2 (add w9#1 w8#1)
```

```
(set w8 (add w9 w8)
```

```
add w8, w9, w8
```

```
2801080b
```

IDA’s microcode

Overview

- Machine code transformed into “microinstructions”
    - 72 unique operations
    - Single-purpose, simple in nature
    - No side effects
- Inspired by ideas from “Reverse Compilation Techniques”

IDA’s microcode

Microinstruction anatomy

Microinstruction

```
add x0.8, t2.8, t2.8
```

IDA’s microcode

Microinstruction anatomy

Microinstruction

```
add x0.8, t2.8, t2.8
```

Operation

`t2.8` = `add` `x0.8` `t2.8`

IDA’s microcode

A basic example

AArch64 assembly

```
ldr x0, [x0, #8]
```

```
ret
```

IDA’s microcode

A basic example

AArch64 assembly

```
ldr x0, [x0, #8]
```

→

IDA’s microcode

A basic example

AArch64 assembly

```
ldr x0, [x0, #8]
```

Generated microcode

```
mov #8.8, t2.8
```

IDA’s microcode

A basic example

AArch64 assembly

```
ldr x0, [x0, #8]
```

Generated microcode

```
mov #8.8, t2.8
```

```
add x0.8, t2.8, t2.8
```

IDA’s microcode

A basic example

Generated microcode

```
mov #8.8, t2.8
add x0.8, t2.8, t2.8
ldx t2.8, t1.8
```

AArch64 assembly

```
ldr x0, [x0, #8]
```

IDA’s microcode

A basic example

AArch64 assembly

```
ldr x0, [x0, #8]
```

Generated microcode

```
mov #8.8, t2.8
add x0.8, t2.8, t2.8
ldx t2.8, t1.8
mov t1.8, x0.8
```

IDA’s microcode

Microcode lifecycle

- Unoptimized, initial lift (Level 1)
- Easy wins (Level 2)
- Local optimizations, function calls (Levels 3, 4)
- Global optimizations (Levels 5–7)
- Local variable analysis (Level 8)

IDA’s microcode

Optimizations visualized

AArch64 assembly

```
ldr x0, [x0, #8]
```

Generated microcode

```
mov #8.8, t2.8
add x0.8, t2.8, t2.8
ldx t2.8, t1.8
mov t1.8, x0.8
```

IDA’s microcode

Optimizations visualized

AArch64 assembly

```
ldr x0, [x0, #8]
```

→

```
ldx (x0.8 + #8.8), t1.8
```

```
mov t1.8, x0.8
```

IDA’s microcode

Optimizations visualized

AArch64 assembly

```
ldr x0, [x0, #8]
```

→

Optimized microcode

```
ldx (x0.8 + #8.8), x0.8
```

IDA’s microcode

Optimizations visualized

AArch64 assembly

```
ldr x0, [x0, #8]
```

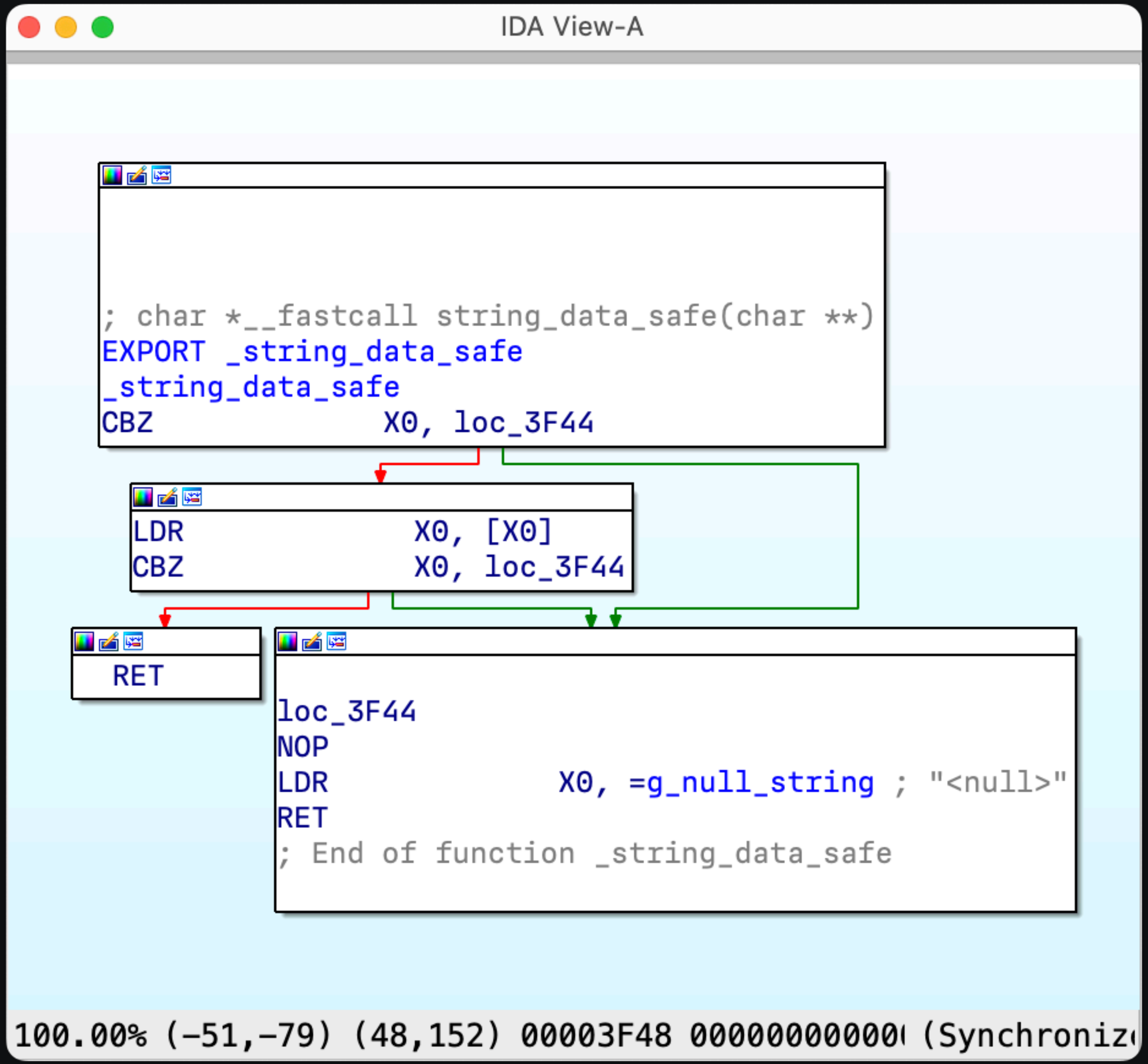
→

Optimized microcode with local variables

```
ldx (a1.8 + #8.8), result.8
```

IDA’s microcode

A real-world example



```
; char *__fastcall string_data_safe(char **)
EXPORT _string_data_safe
_string_data_safe
CBZ             X0, loc_3F44
```

```
LDR             X0, [X0]
CBZ             X0, loc_3F44
```

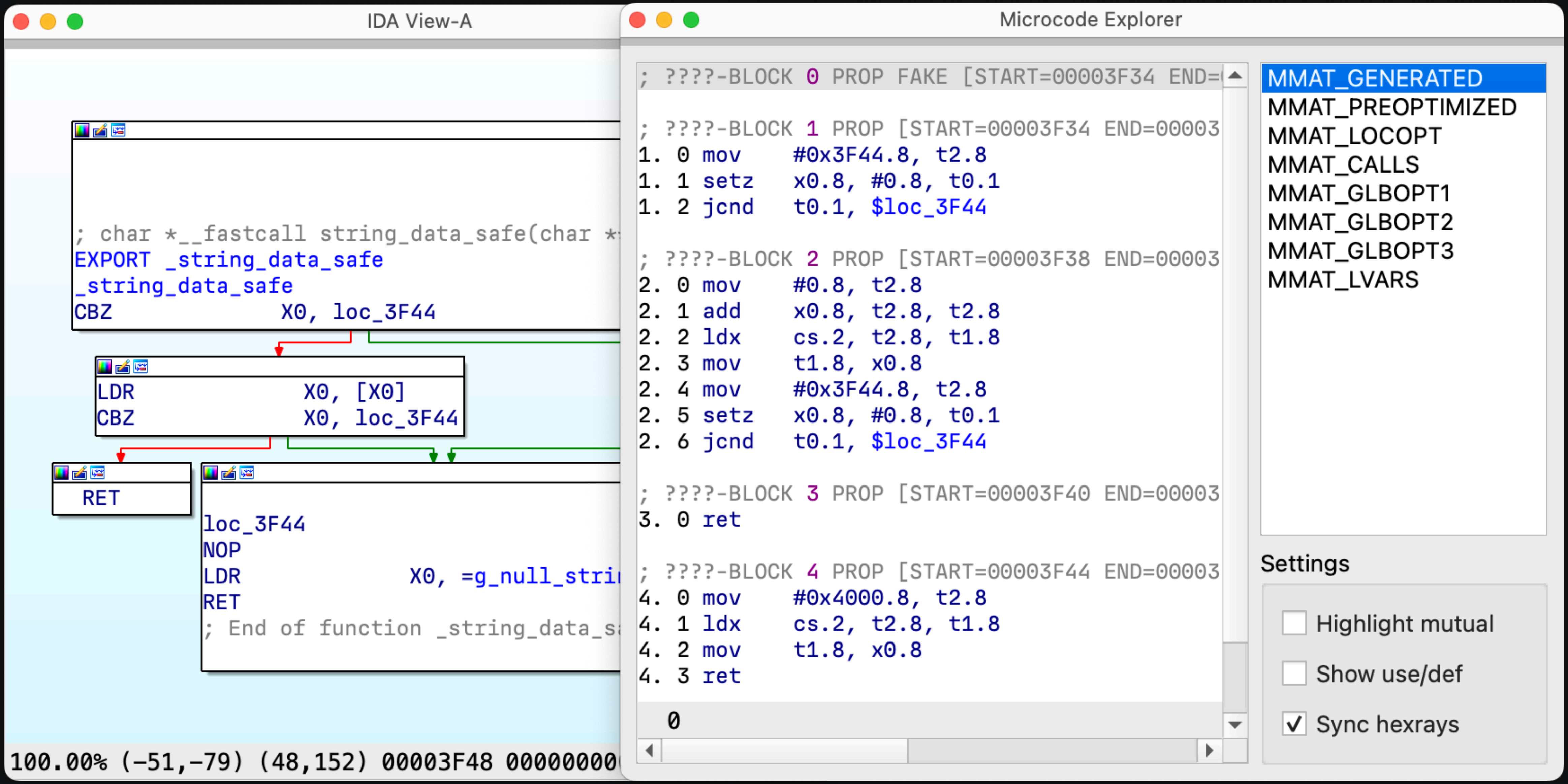
```
RET
```

```
loc_3F44
NOP
LDR             X0, =g_null_string ; "<null>"
RET
; End of function _string_data_safe
```

```
100.00% (-51,-79) (48,152) 00003F48 00000000000 (Synchroniz
```

IDA’s microcode

A real-world example



```
; char *__fastcall string_data_safe(char *
EXPORT _string_data_safe
_string_data_safe
CBZ                X0, loc_3F44

LDR                X0, [X0]
CBZ                X0, loc_3F44

RET

loc_3F44
NOP
LDR                X0, =g_null_stri
RET
; End of function _string_data_s
```

```
100.00% (-51,-79) (48,152) 00003F48 00000000
```

```
; ????-BLOCK 0 PROP FAKE [START=00003F34 END=

; ????-BLOCK 1 PROP [START=00003F34 END=00003
1. 0 mov     #0x3F44.8, t2.8
1. 1 setz    x0.8, #0.8, t0.1
1. 2 jcnd    t0.1, $loc_3F44

; ????-BLOCK 2 PROP [START=00003F38 END=00003
2. 0 mov     #0.8, t2.8
2. 1 add     x0.8, t2.8, t2.8
2. 2 ldx     cs.2, t2.8, t1.8
2. 3 mov     t1.8, x0.8
2. 4 mov     #0x3F44.8, t2.8
2. 5 setz    x0.8, #0.8, t0.1
2. 6 jcnd    t0.1, $loc_3F44

; ????-BLOCK 3 PROP [START=00003F40 END=00003
3. 0 ret

; ????-BLOCK 4 PROP [START=00003F44 END=00003
4. 0 mov     #0x4000.8, t2.8
4. 1 ldx     cs.2, t2.8, t1.8
4. 2 mov     t1.8, x0.8
4. 3 ret

  0
```

- MMAT_GENERATED
- MMAT_PREOPTIMIZED
- MMAT_LOCOPT
- MMAT_CALLS
- MMAT_GLBOPT1
- MMAT_GLBOPT2
- MMAT_GLBOPT3
- MMAT_LVARS

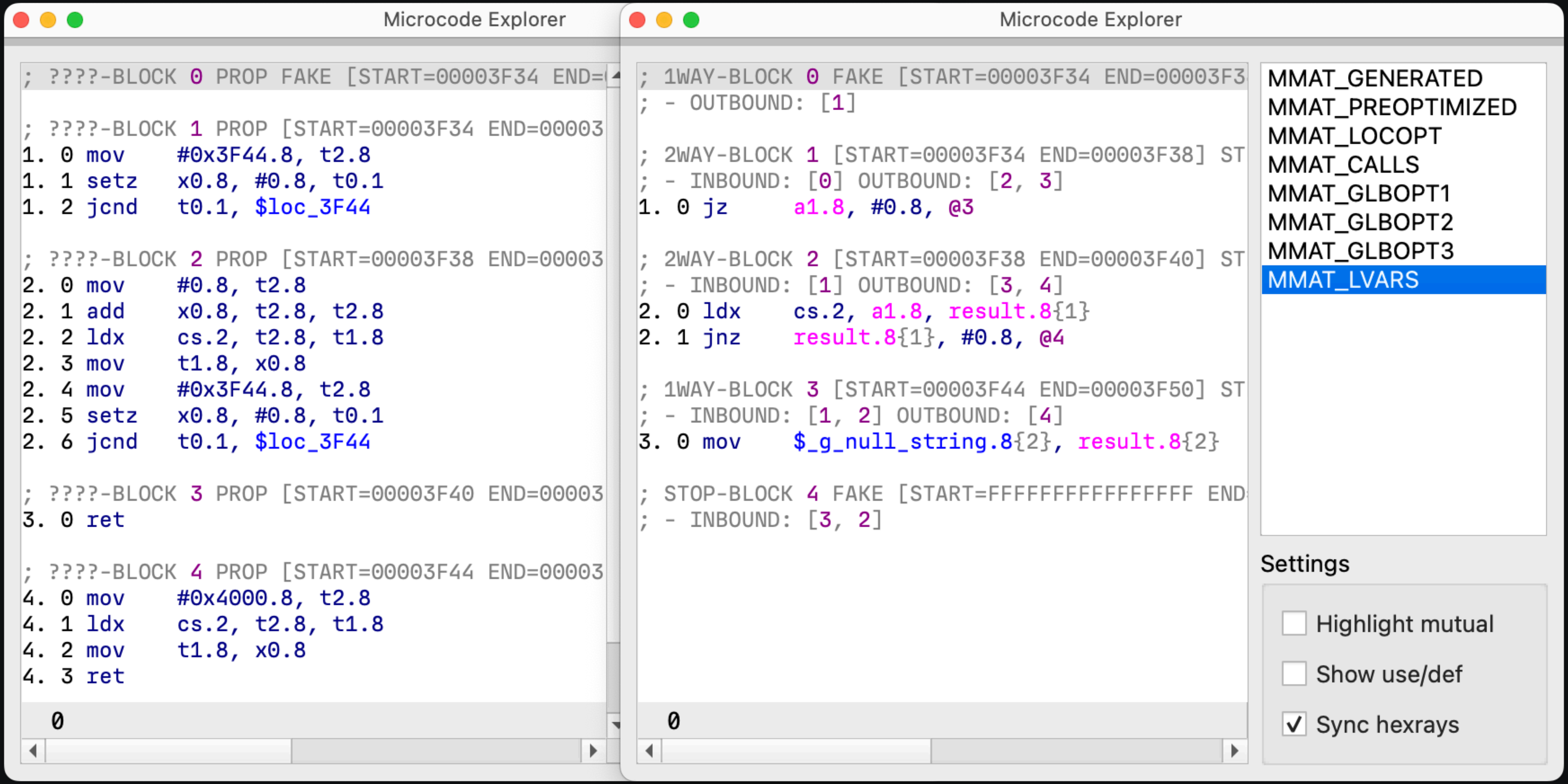
Settings

☐ Highlight mutual
☐ Show use/def
☑ Sync hexrays

Microcode shown with the “Lucid” plugin by Markus Gassedelen. (https://github.com/gaasedelen/lucid)

IDA’s microcode

A real-world example



```
; ????-BLOCK 0 PROP FAKE [START=00003F34 END=

; ????-BLOCK 1 PROP [START=00003F34 END=00003
1. 0 mov     #0x3F44.8, t2.8
1. 1 setz    x0.8, #0.8, t0.1
1. 2 jcnd    t0.1, $loc_3F44

; ????-BLOCK 2 PROP [START=00003F38 END=00003
2. 0 mov     #0.8, t2.8
2. 1 add     x0.8, t2.8, t2.8
2. 2 ldx     cs.2, t2.8, t1.8
2. 3 mov     t1.8, x0.8
2. 4 mov     #0x3F44.8, t2.8
2. 5 setz    x0.8, #0.8, t0.1
2. 6 jcnd    t0.1, $loc_3F44

; ????-BLOCK 3 PROP [START=00003F40 END=00003
3. 0 ret

; ????-BLOCK 4 PROP [START=00003F44 END=00003
4. 0 mov     #0x4000.8, t2.8
4. 1 ldx     cs.2, t2.8, t1.8
4. 2 mov     t1.8, x0.8
4. 3 ret
```

0

```
; 1WAY-BLOCK 0 FAKE [START=00003F34 END=00003F3
; - OUTBOUND: [1]

; 2WAY-BLOCK 1 [START=00003F34 END=00003F38] ST
; - INBOUND: [0] OUTBOUND: [2, 3]
1. 0 jz      a1.8, #0.8, @3

; 2WAY-BLOCK 2 [START=00003F38 END=00003F40] ST
; - INBOUND: [1] OUTBOUND: [3, 4]
2. 0 ldx     cs.2, a1.8, result.8{1}
2. 1 jnz     result.8{1}, #0.8, @4

; 1WAY-BLOCK 3 [START=00003F44 END=00003F50] ST
; - INBOUND: [1, 2] OUTBOUND: [4]
3. 0 mov     $_g_null_string.8{2}, result.8{2}

; STOP-BLOCK 4 FAKE [START=FFFFFFFFFFFFFFFF END
; - INBOUND: [3, 2]
```

0

Settings

☐ Highlight mutual
☐ Show use/def
☑ Sync hexrays

Microcode shown with the “Lucid” plugin by Markus Gassedelen. (https://github.com/gaasedelen/lucid)

Ghidra’s p-code

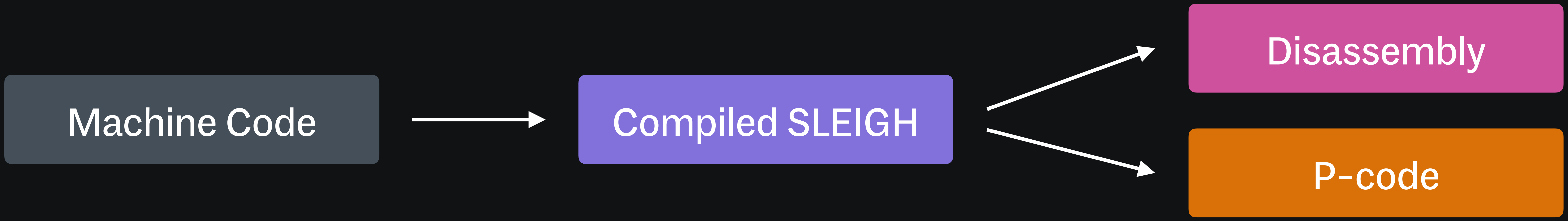
Overview

- Self-described register transfer language
- Similar to IDA’s microcode
  - 62 unique operations
  - Mostly free of side-effects
  - etc…

Ghidra’s p-code

SLEIGH

- Expressive language for describing ISAs
    - Does both disassembly and lifting
- Inspired by SLED (AT&T Labs, 1997)
- Lots of moving parts



Machine Code

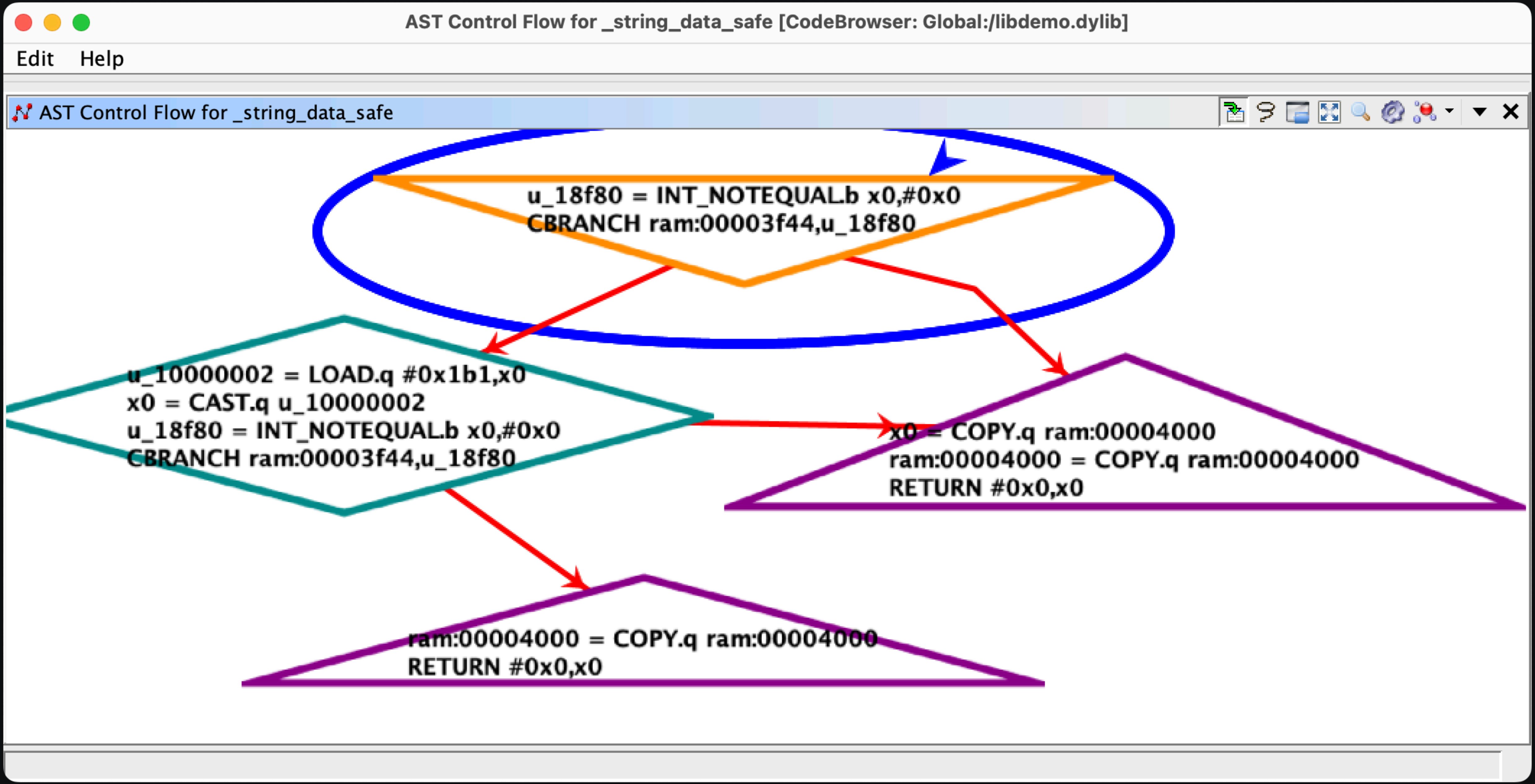
Compiled SLEIGH

Disassembly

P-code

Ghidra’s p-code

A real-world example



```
u_18f80 = INT_NOTEQUAL.b x0,#0x0
CBRANCH ram:00003f44,u_18f80
```

```
u_10000002 = LOAD.q #0x1b1,x0
x0 = CAST.q u_10000002
u_18f80 = INT_NOTEQUAL.b x0,#0x0
CBRANCH ram:00003f44,u_18f80
```

```
x0 = COPY.q ram:00004000
ram:00004000 = COPY.q ram:00004000
RETURN #0x0,x0
```

```
ram:00004000 = COPY.q ram:00004000
RETURN #0x0,x0
```

Binary Ninja’s ILs

Overview

- Stack of three intermediate languages (ILs)
  - Low-level IL (LLIL)
  - Medium-level IL (MLIL)
  - High-level IL (HLIL)
- Tree/expression-based

Disassembly

LLIL

MLIL

HLIL

Binary Ninja’s ILs

Low-level IL

- 108 unique operations
- Most primitive user-facing IL, lifted from machine code
  - Internally, “Lifted IL” technically comes first
- No concept of memory
- Resolved flags & stack pointer

Binary Ninja’s ILs

Medium-level IL

- Much more expressive than LLIL
  - Introduces variables, types, calls/parameters
- Acts as the medium for lots of important analysis
  - Type propagation
  - Data flow & value set analysis
  - Other important things

Binary Ninja’s ILs

High-level IL

- Looks closer to C/pseudocode
- Refined through numerous simplification passes
- Introduces semantic control flow
- Adds variable merging
- Dead code elimination
- Etc…

Binary Ninja’s ILs

Anatomy of an IL instruction

- Text form
- Tree form
    - Operation
    - Variation of operands
        - Source & destination
        - Left & right
        - Etc…

Binary Ninja's ILs

A basic example

AArch64 assembly

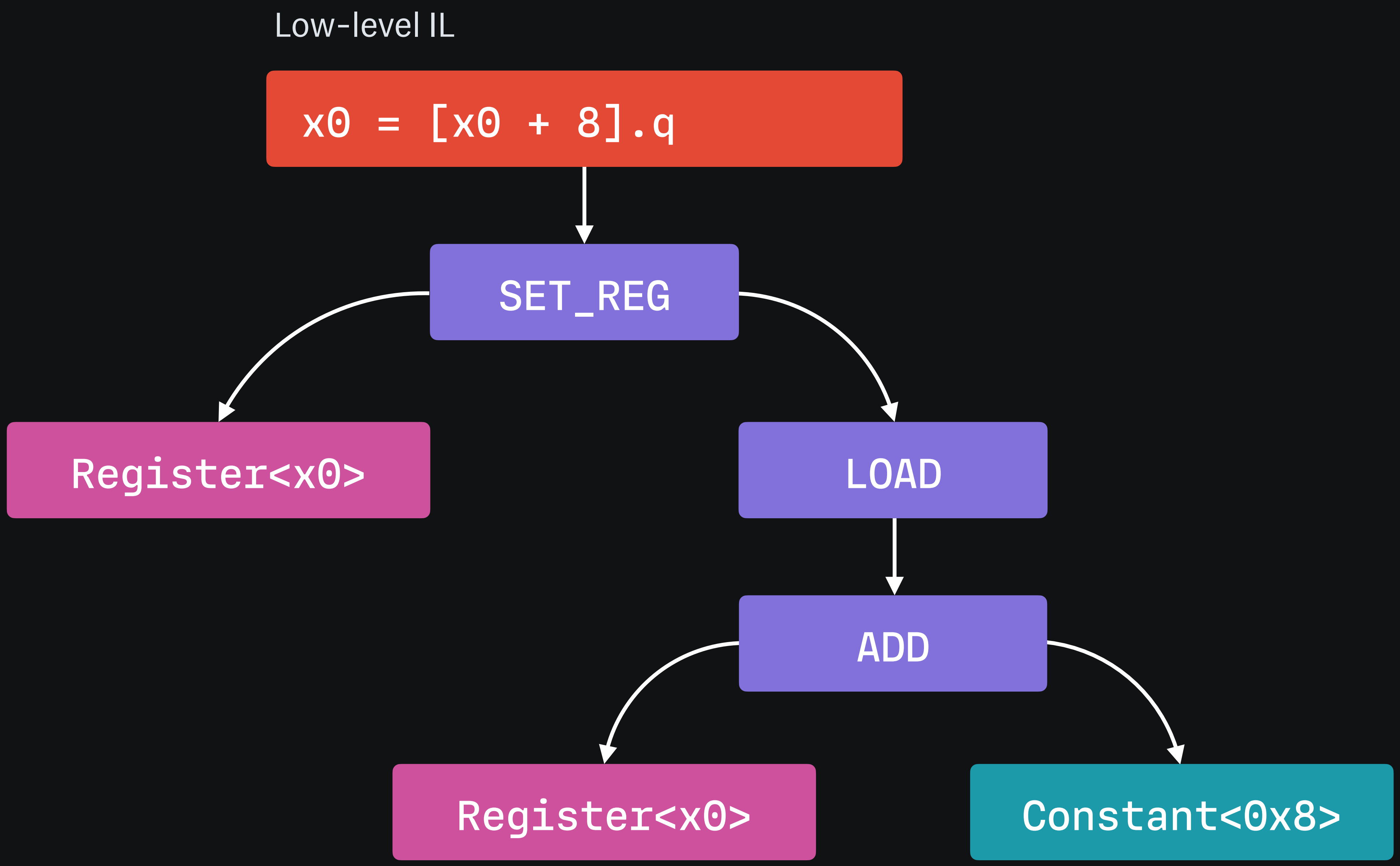
```
ldr x0, [x0, #8]
```

Low-level IL (text-form)

```
x0 = [x0 + 8].q
```

Binary Ninja's ILs

A basic example



Low-level IL

`x0 = [x0 + 8].q`

SET_REG

Register<x0>

LOAD

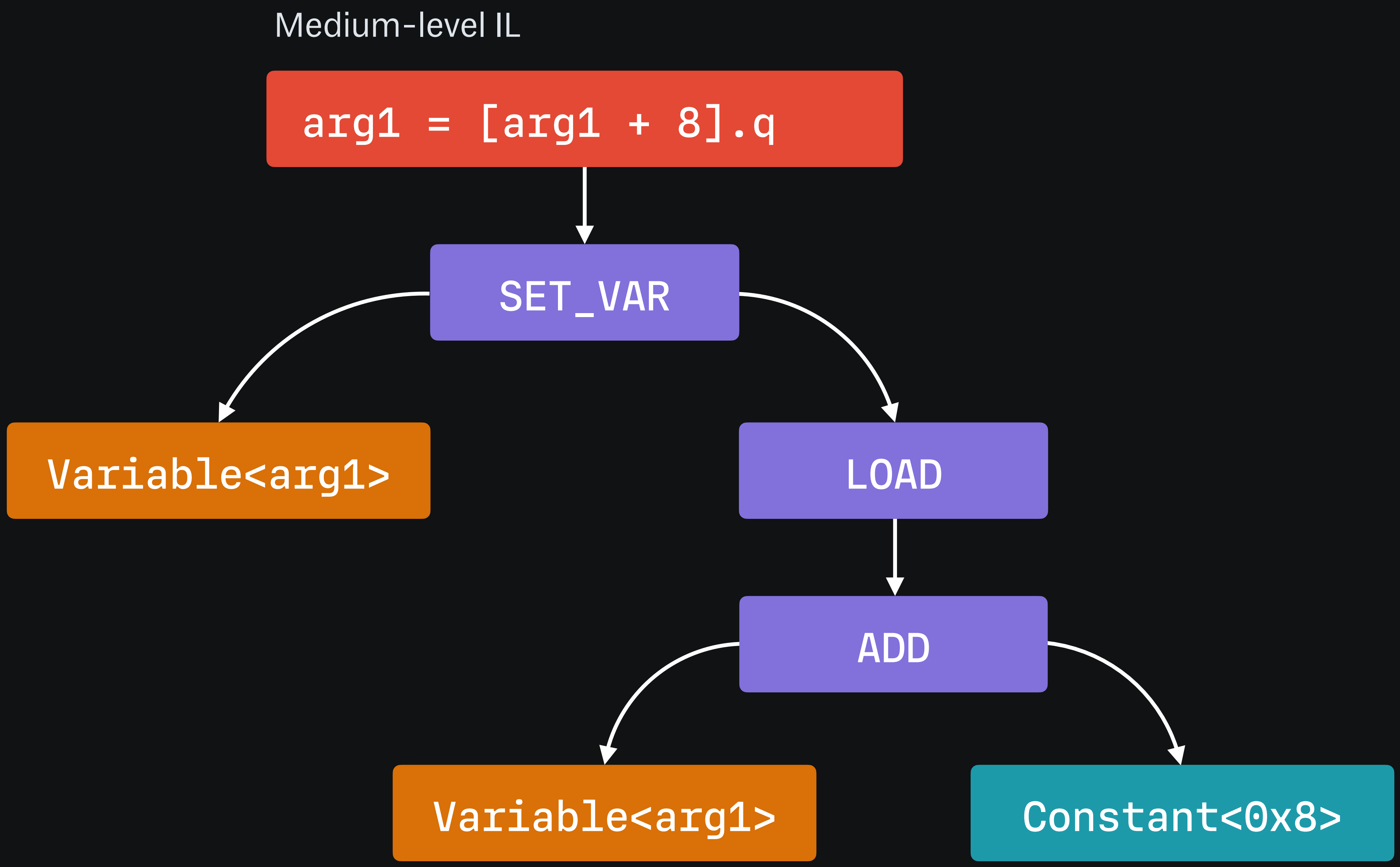
ADD

Register<x0>

Constant<0x8>

Binary Ninja's ILs

A basic example


Medium-level IL

`arg1 = [arg1 + 8].q`

SET_VAR

Variable<arg1>

LOAD

ADD

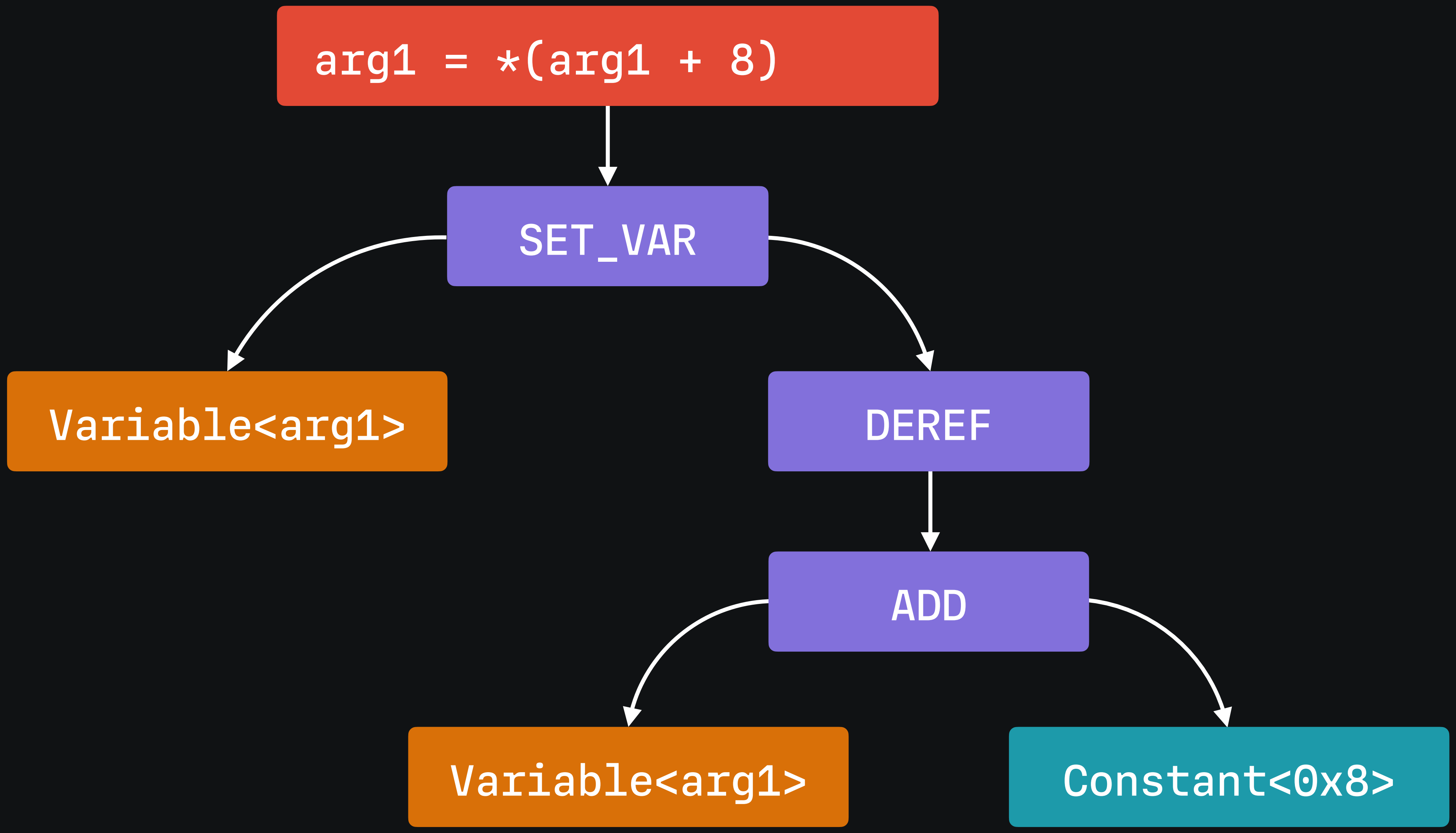
Variable<arg1>

Constant<0x8>

Binary Ninja’s ILs

A basic example

High-level IL



`arg1 = *(arg1 + 8)`

SET_VAR

Variable<arg1>

DEREF

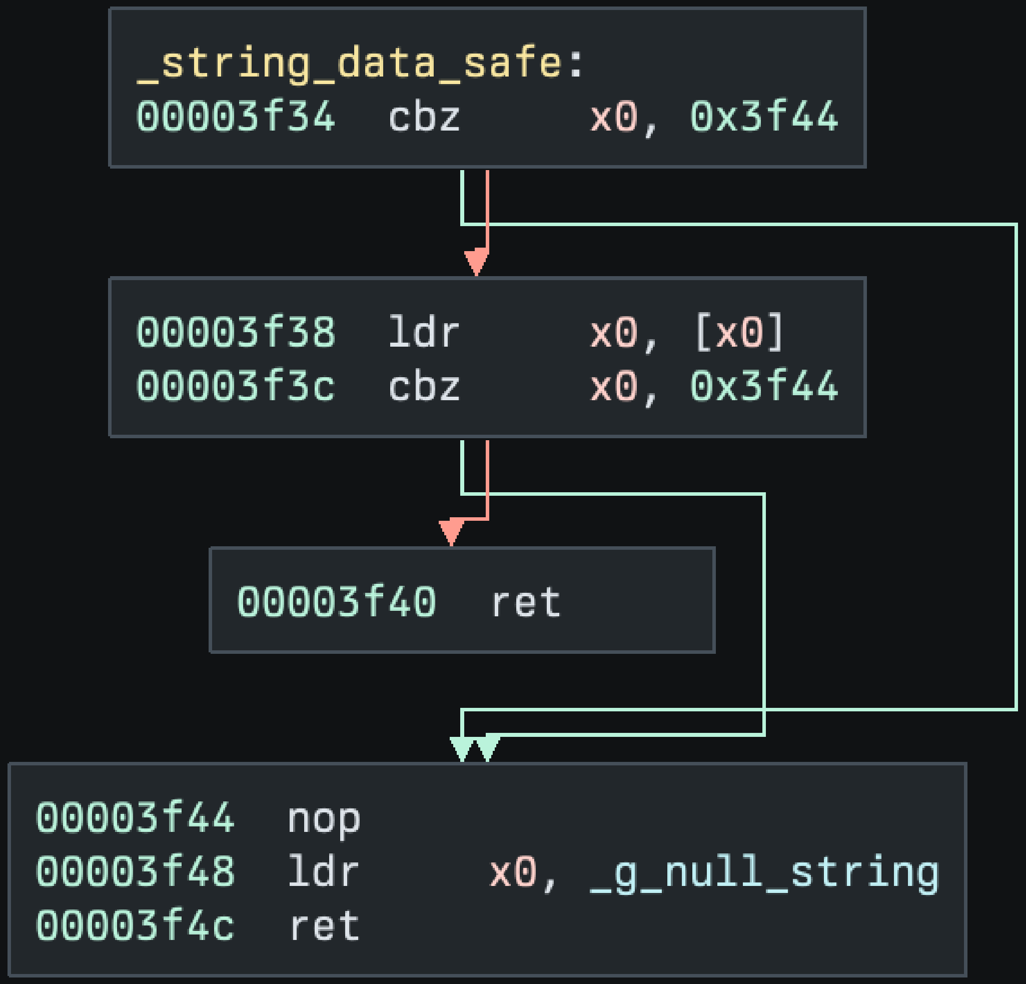
ADD

Variable<arg1>

Constant<0x8>

Binary Ninja’s ILs

A real-world example: disassembly



```
_string_data_safe:
00003f34  cbz     x0, 0x3f44
```

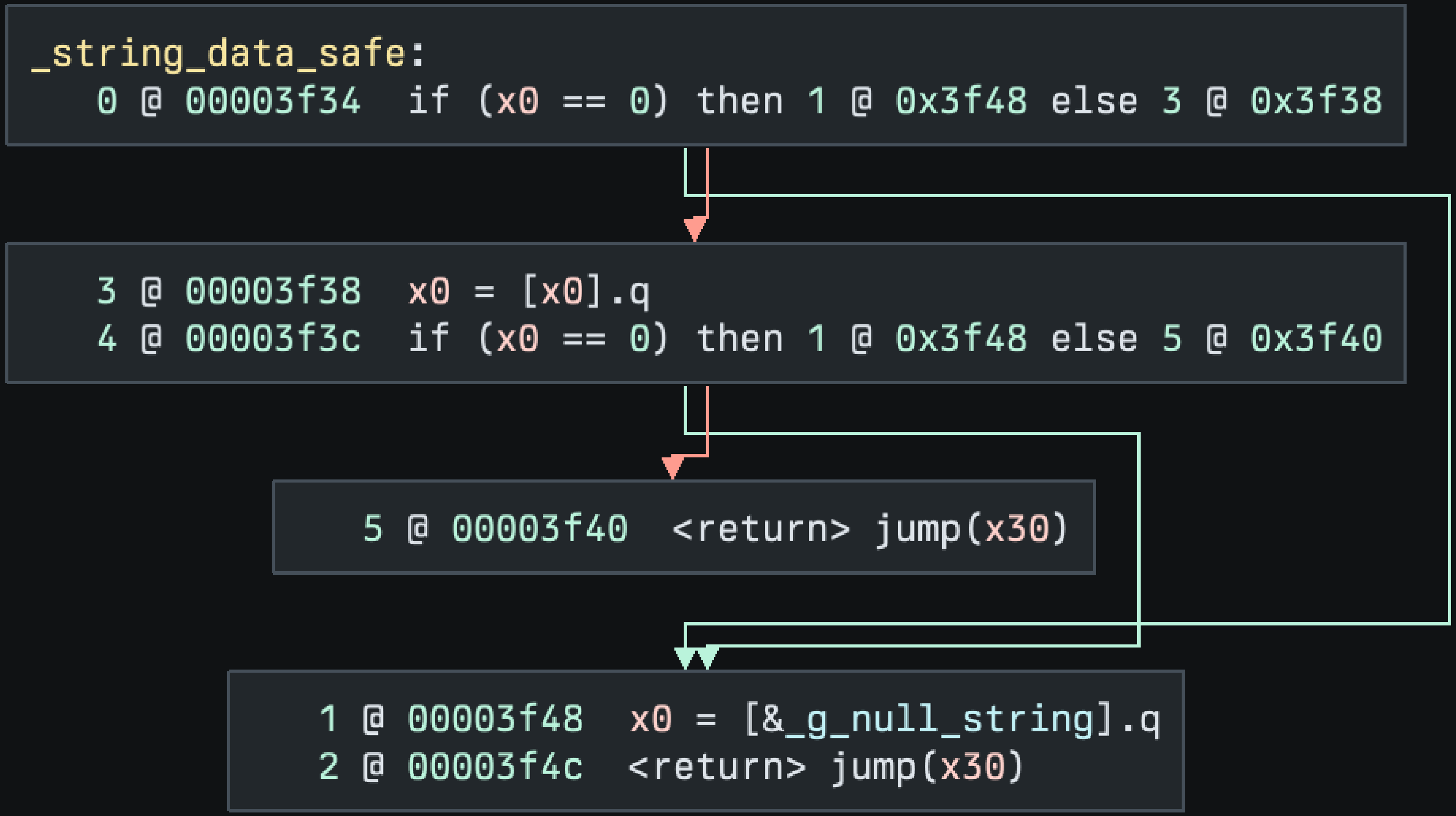
```
00003f38  ldr     x0, [x0]
00003f3c  cbz     x0, 0x3f44
```

```
00003f40  ret
```

```
00003f44  nop
00003f48  ldr     x0, _g_null_string
00003f4c  ret
```

Binary Ninja's ILs

A real-world example: LLIL



```
_string_data_safe:
   0 @ 00003f34  if (x0 == 0) then 1 @ 0x3f48 else 3 @ 0x3f38
```

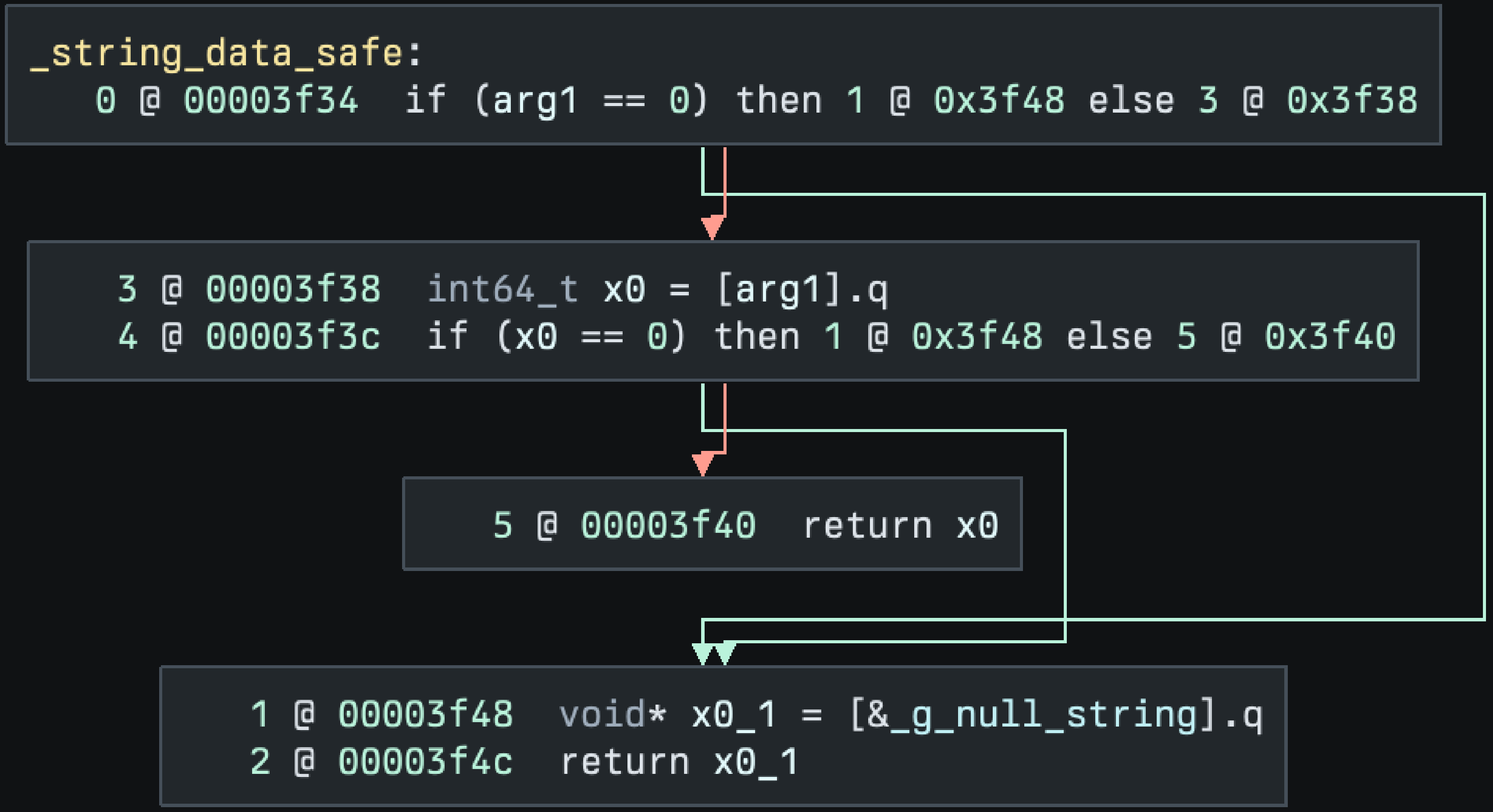
```
   3 @ 00003f38  x0 = [x0].q
   4 @ 00003f3c  if (x0 == 0) then 1 @ 0x3f48 else 5 @ 0x3f40
```

```
   5 @ 00003f40  <return> jump(x30)
```

```
   1 @ 00003f48  x0 = [&_g_null_string].q
   2 @ 00003f4c  <return> jump(x30)
```

Binary Ninja’s ILs

A real-world example: MLIL



```
_string_data_safe:
   0 @ 00003f34  if (arg1 == 0) then 1 @ 0x3f48 else 3 @ 0x3f38
```

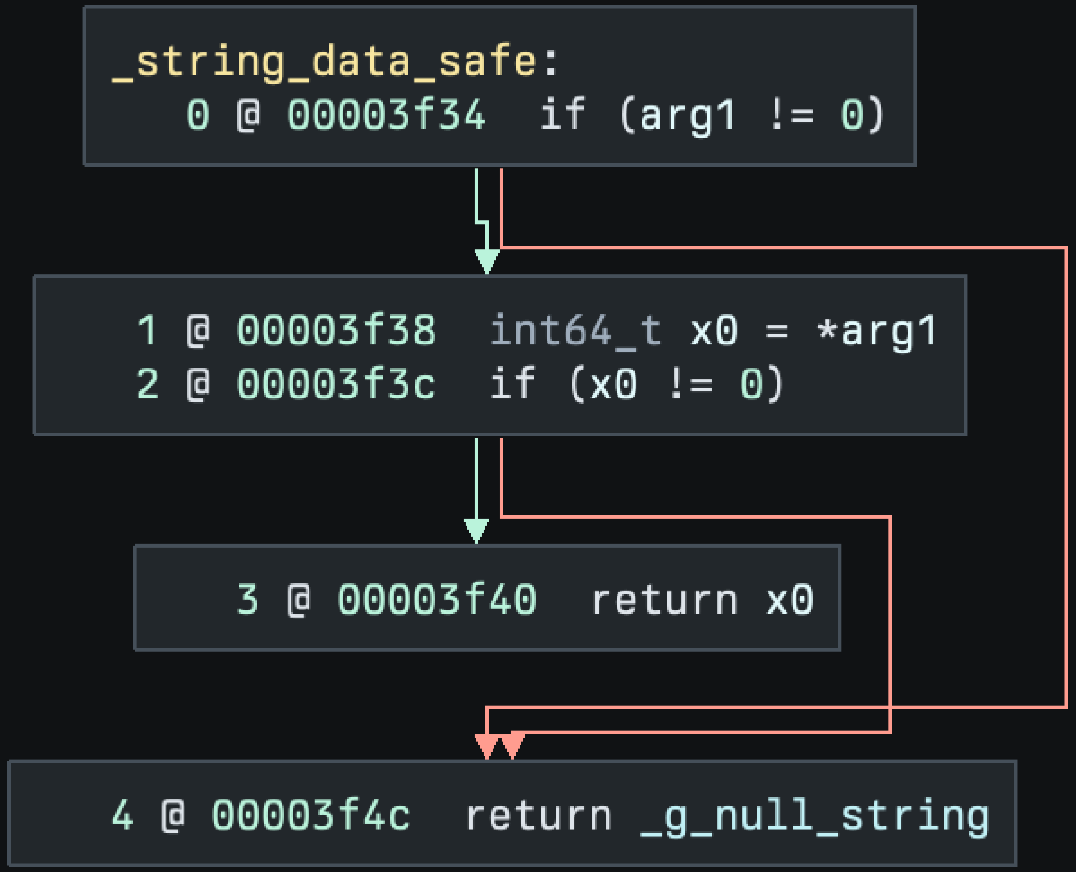
```
   3 @ 00003f38  int64_t x0 = [arg1].q
   4 @ 00003f3c  if (x0 == 0) then 1 @ 0x3f48 else 5 @ 0x3f40
```

```
   5 @ 00003f40  return x0
```

```
   1 @ 00003f48  void* x0_1 = [&_g_null_string].q
   2 @ 00003f4c  return x0_1
```

Binary Ninja’s ILs

A real-world example: HLIL



```
_string_data_safe:
   0 @ 00003f34  if (arg1 != 0)
```

```
   1 @ 00003f38  int64_t x0 = *arg1
   2 @ 00003f3c  if (x0 != 0)
```

```
   3 @ 00003f40  return x0
```

```
   4 @ 00003f4c  return _g_null_string
```

Aside

Immediate vs. deferred flags

- Immediate flags
    - IDA
    - Ghidra
- Deferred flags
    - Binary Ninja

Aside

What about LLVM IR..?

- Has some apparent advantages
  - Popularity, infrastructure, maturity, etc.
- Harder to lift to straight from assembly
- Missing important decompilation-oriented semantics

Data flow analysis

Classic techniques (IDA)

- Tried-and-true compiler techniques
  - Value set analysis
  - Use-def chains
  - (Global) copy propagation
  - Etc...

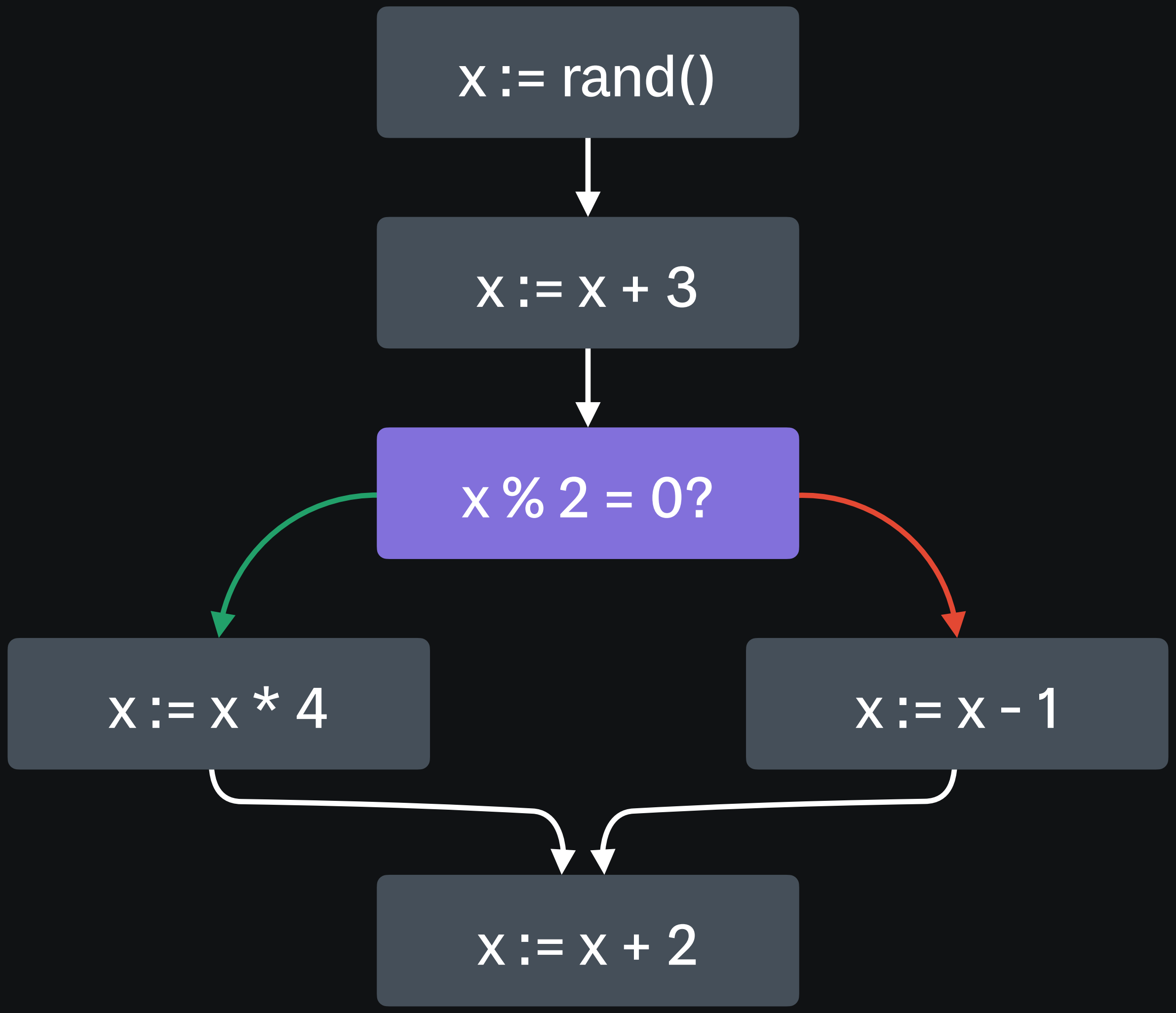
Data flow analysis

Static single assignment form (Binary Ninja & Ghidra)

- Every variable has exactly one definition
  - Subsequent assignments labeled with subscripts
    - e.g. x_2
- Joining of two live variables denoted with Phi (Φ)
  - e.g. $\Phi(x_2, x_3)$
- It’s easier to understand visually…

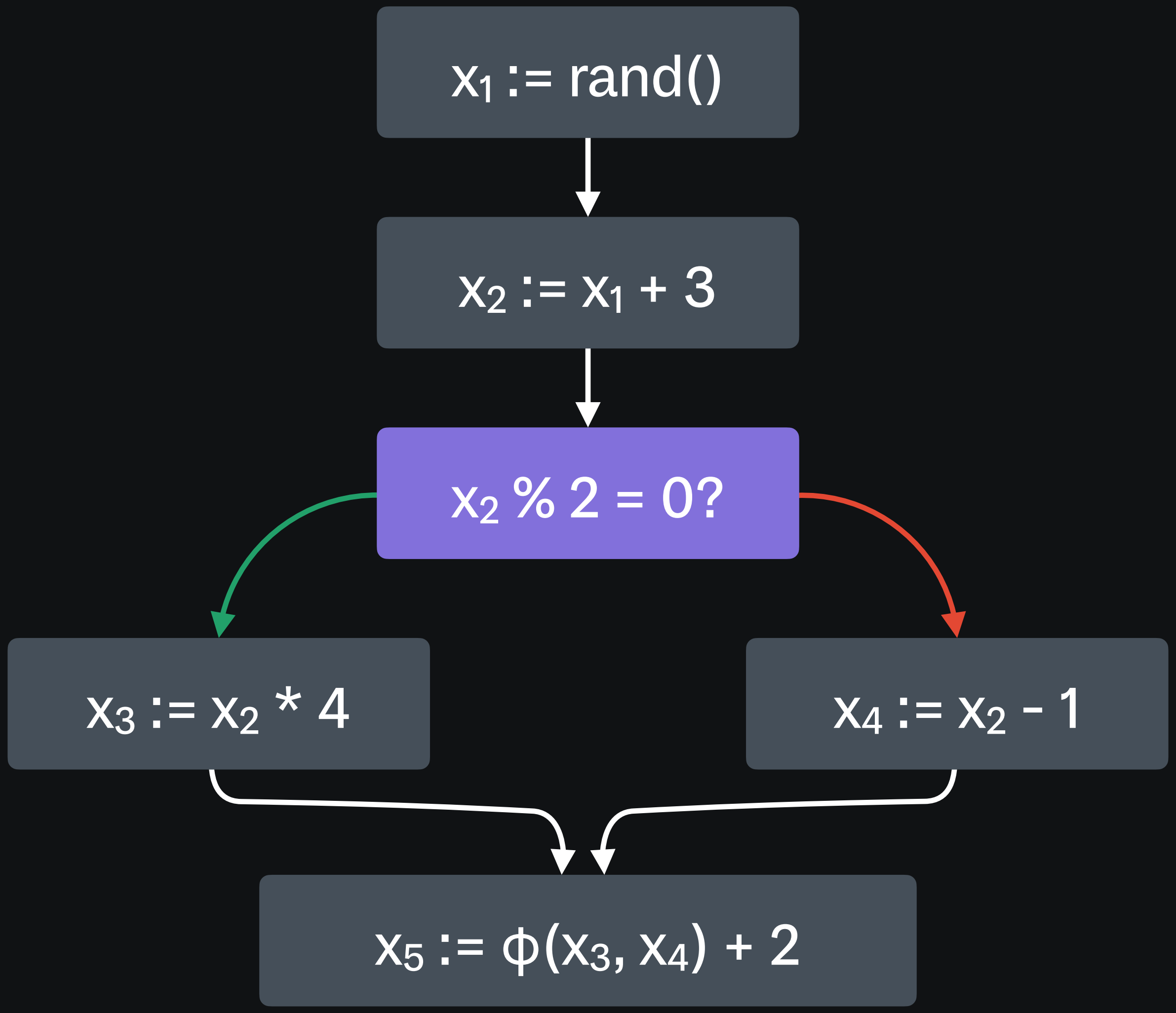
Data flow analysis

Non-SSA form example



Data flow analysis

SSA form example



$x_1 := \mathrm{rand}()$

$x_2 := x_1 + 3$

$x_2 \% 2 = 0?$

$x_3 := x_2 * 4$

$x_4 := x_2 - 1$

$x_5 := \phi(x_3, x_4) + 2$

Data flow analysis

Real-world SSA form example

```
_example_ssa_small:
00003f10  sub     sp, sp, #0x20
00003f14  stp     x29, x30, [sp, #0x10] {__saved_x29} {__saved_x30}
00003f18  add     x29, sp, #0x10 {__saved_x29}
00003f1c  bl      _rand
00003f20  stur    w0, [x29, #-0x4 {var_14}]
00003f24  ldur    w8, [x29, #-0x4 {var_14}]
00003f28  add     w8, w8, #0x3
00003f2c  stur    w8, [x29, #-0x4 {var_14_1}]
00003f30  ldur    w9, [x29, #-0x4 {var_14_1}]
00003f34  ldur    w8, [x29, #-0x4 {var_14_1}]
00003f38  tbnz    w9, #0, 0x3f44
```

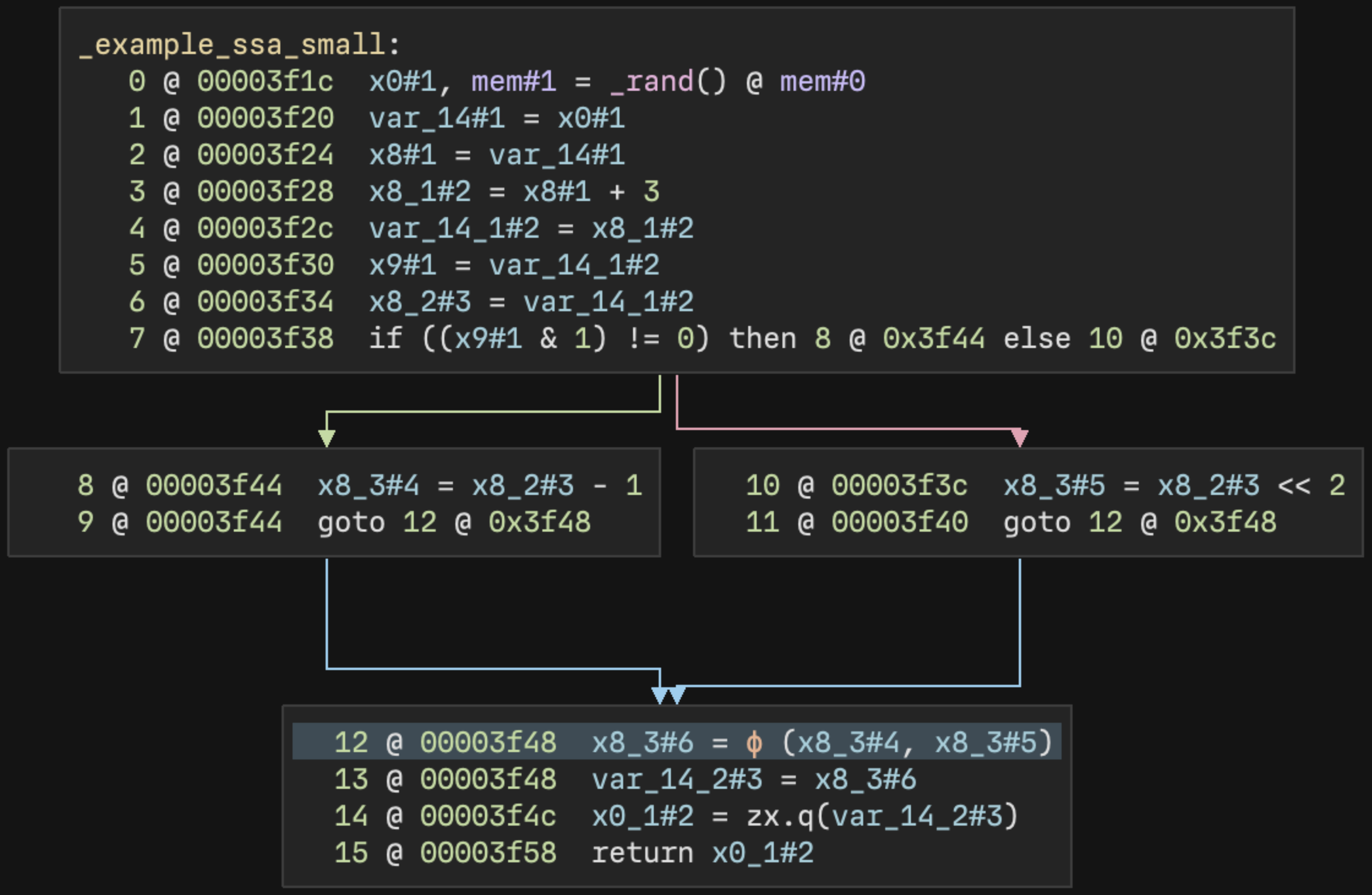
```
00003f44  sub     w8, w8, #0x1
```

```
00003f3c  lsl     w8, w8, #0x2
00003f40  b       0x3f48
```

```
00003f48  stur    w8, [x29, #-0x4 {var_14_2}]
00003f4c  ldur    w0, [x29, #-0x4 {var_14_2}]
00003f50  ldp     x29, x30, [sp, #0x10] {__saved_x29} {__saved_x30}
00003f54  add     sp, sp, #0x20
00003f58  ret
```

Data flow analysis

Real-world SSA form example



```
_example_ssa_small:
   0 @ 00003f1c  x0#1, mem#1 = _rand() @ mem#0
   1 @ 00003f20  var_14#1 = x0#1
   2 @ 00003f24  x8#1 = var_14#1
   3 @ 00003f28  x8_1#2 = x8#1 + 3
   4 @ 00003f2c  var_14_1#2 = x8_1#2
   5 @ 00003f30  x9#1 = var_14_1#2
   6 @ 00003f34  x8_2#3 = var_14_1#2
   7 @ 00003f38  if ((x9#1 & 1) != 0) then 8 @ 0x3f44 else 10 @ 0x3f3c
```

```
   8 @ 00003f44  x8_3#4 = x8_2#3 - 1
   9 @ 00003f44  goto 12 @ 0x3f48
```

```
   10 @ 00003f3c  x8_3#5 = x8_2#3 << 2
   11 @ 00003f40  goto 12 @ 0x3f48
```

```
   12 @ 00003f48  x8_3#6 = ϕ (x8_3#4, x8_3#5)
   13 @ 00003f48  var_14_2#3 = x8_3#6
   14 @ 00003f4c  x0_1#2 = zx.q(var_14_2#3)
   15 @ 00003f58  return x0_1#2
```

Closing thoughts

Modern decompilation challenges

- Unrepresentable instructions
- Inlining, outlining
- Pointer & length strings
- Pointer misconceptions
- Weird calling conventions
- Much more…

Closing thoughts

Modern language construct support

- Modern code generation is increasingly intricate
    - Swift
    - Rust
    - Firebloom (-fbounds-safety)
- Need to filter signal from noise

Closing thoughts

Decompile as X?

- Not everything is written in C anymore
  - Why do we try to decompile everything to C?
  - Should we still decompile everything as C?

Closing thoughts

Diverging goals in decompilation

- Literal decompilation?
- Semantic decompilation?
- Answer: Abstraction/optimization problem

Closing thoughts

Modularity & tuning

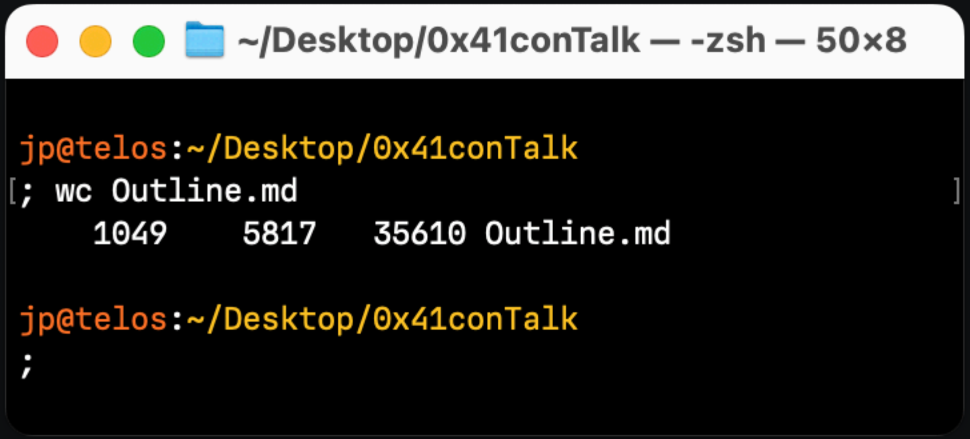
- Soon-to-be necessity
- “One size fits all” decompilation is aging poorly
  - Need to be lean, adaptable
  - What will the next ten years hold?

Demo time?

a.k.a “how long did those slides take?”

Thank you!

- Questions?
- Find me after if you want to chat more
  - Not everything made it into the slides :)



```
jp@telos:~/Desktop/0x41conTalk
[; wc Outline.md                                   ]
    1049    5817   35610 Outline.md

jp@telos:~/Desktop/0x41conTalk
;
```

- Twitter: @jonpalmisc
- Mastodon: @jonpalmisc@infosec.exchange